

Mars Express MARSIS Radar: A Prediction of the Effect of Overlying Ice on Detecting Polar Basal Lakes and Inter-Glacial Aquifers

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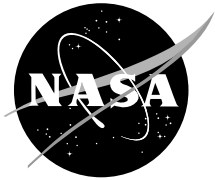
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Abstract

The penetration of the MARSIS radar signal into the polar ice mass is modeled to determine the capability of the instrument to locate sub-glacial aquifers. As a ground penetrating radar, the orbiting MARSIS transmits a signal > 1 W between 1-5 MHz. In this work we will investigate the effect of ice conductive losses on the radar-detection of subsurface aquifers. Based on wave propagation analysis, it is found that for a bulk ice conductivity below 10^{-5} S/m, conductive losses in the medium are not significant. However, if the bulk ice conductivity is relatively large ($> 10^{-5}$ S/m), the reflected signal from any deep aquifer will be absorbed as it propagates in the lossy ice medium limiting the probing depth.

Introduction

A primary science goal of the Mars Exploration Program (MEP) is the search for subsurface water. The Mars Express/Mars Advanced Radar for Subsurface and Ionospheric Sounding (MEX/MARSIS) is a subsurface radio sounding system currently on its way to Mars, arriving in late 2003, that can transmit and receive signals in a range between 0.1-5.5 MHz with peak power levels near 10 W. The primary science goal of the investigation is to map the distribution of water, both liquid and solid form, in the upper portions of Mars's crust. The anticipated probing depth of the subsurface sounder is between 0.1-5 km, depending upon conditions. This depth range is fairly broad, and it would be desirable to quantify more exactly the expected probing depth in the polar ice mass regions. In essence, we present a simple feasibility study in order to better establish expectations for the success of the low power MARSIS subsurface sounding in the Martian polar regions. In this work, the effect of the icy conductive medium on signal attenuation will be examined.

Basal lakes are defined as water reservoirs formed at the underside of an ice mass. For example, such lakes are found at the ice/rock interface under the Antarctic ice cap [Oswald and Robin, 1973]. Clifford [1987, 1993] has described the possibility of such basal lake formation under the Martian polar cap (defined as the remnant water ice cap and underlying dusty-ice layered deposits) via melting from ice insulation effects, local geothermal hot spots, or heat-generating glacial sliding. Ice cap basal melting may be an important process in the Martian hydrological cycle [Clifford, 1993, 2003]. Such melts may feed a quasi-global water table located many kilometers below the surface. Via diffusion processes, this deep water is proposed to migrate to the surface forming a thick ice layer called the cryosphere. Evidence for the surface ice layer was recently obtained by Mars Odyssey gamma ray and neutron (GRS) detectors [Boynton et al, 2002; Mitrofanov et al., 2002; Feldman et al., 2002].

Since basal lakes may be a primary element of the Martian water cycle [Clifford, 1993, 2003], they represent a key target for MARSIS during its polar overpass. There are significant periods when the MEX periapsis is nearly directly over the nighttime Martian poles. During these times, ionosphere attenuation is minimized and a direct radio sounding of the polar ice caps is possible. However, the ability to return a signal from a deep aquifer is a strong function of a number of variables, including overlying ice conductivity, which is currently unknown. In this letter, we will examine the feasibility of detecting the ice cap base given various cap top-layer compositions.

MEX and MARSIS Description

Mars Express was successfully launched on 2 June 2003 and is planned for 24 December 2003 orbit insertion about the planet. The anticipated mission is 1 Martian year (687 days). The 86° eccentric orbit ranges from a periapsis of 279 km to an apoapsis of 11634 km. The initial latitude of periapsis is anticipated to be at the equator and this periapsis latitude will drift by about 0.5 degrees per sol. Over the course of the mission, the periapsis location will migrate over both poles during favorable periods when they are unlit (i.e., the intervening ionosphere density is low). These ideal dates are near June 2004 for south polar soundings and April 2005 for north polar soundings.

The MARSIS instrument consists of a 40-m antenna transmitter/receiver system. MARSIS will deploy its 40-m antenna approximately 100 days into the mission. The system has two operating modes: An active ionosphere sounding model (AIS) and subsurface sounding (SS) mode. In the AIS mode, the transmitter will emit wave packets sweeping from 0.1 to 5.5 MHz in order to excite local plasma resonances and investigate wave propagation into the lower altitude ionosphere along the X and O plasma modes. Ionosphere density layers, including those that may form from meteoric impacts [Pesnell and Grebowsky, 2000; Witasse et al., 2001] may be probed via this mode.

In SS mode, the transmitter emits a 1 MHz bandwidth pulse in 4 distinct bands: 1.3-2.3 MHz, 2.5-3.5 MHz, 3.5-4.5 MHz, and 4.5-5.5, MHz. The 40-m antenna will have a resonance frequency at $f_{res} \sim 3.75$ MHz, and transmission near this band will be emitted at peak powers (5-10 W). Below this resonance, transmission power is less efficient a natural consequence of radio transmission via short dipole radiators [Calvert *et al.*, 1995]. MARSIS SS sounding occurs when the spacecraft is below 800 km altitude along its orbital track.

Radar Ionospheric Penetration

The ability of a signal to propagate to the surface depends on the intervening ionospheric plasma density. At wave frequencies below the peak plasma frequency ($f_p = 9000n^{1/2}$, n in el/cc, f_p in Hertz), the ionosphere is opaque to freely-propagating radio signals and there is no direct access to the surface. The dayside density of the Martian ionosphere has values near 10^5 el/cc ($f_p \sim 3$ MHz) but quickly drops to ~ 5000 el/cc (or $f_p \sim 600$ kHz) on the nightside [Zhang, 1990]. This high-to-low density transition occurs within about 10° of the terminator. Hence, on the dayside, only the 4.0 and 5.0 MHz bands of MARSIS will have access to the surface, and this view may be obscured (attenuation and ray distortion) because ionosphere absorption is still present well above f_p [Safaenili *et al.*, 2003]. Methods for removing ionosphere attenuation effects above f_p have been developed [Safaenili *et al.*, 2003] and will be tested during the mission. For transmission frequencies near f_p , large phase distortion is also expected and a method to adaptively compensate for this effect has been developed [Biccari *et al.*, 2001]. However, since the plasma density is expected to drop by a factor of 100 over the night-side, access to the surface may be possible in all MARSIS SS bands. Safaenili *et al.* [2003] indicates that nightside ionospheric absorption at 4 MHz results in only ~ 4 dB of signal loss compared to nearly 20 dB in dayside regions. Thus, for polar studies, examination of the regions during unlit low-altitude over-flights is preferred, during periods when the periapsis is over the nightside pole (like the ideal dates listed above).

Feasibility of Detecting a Polar Aquifer

The MARSIS expectation is to probe the subsurface between 0.3 to 5 km under favorable conditions [MARSIS PS PIP, 2002]. The key question for polar studies is exactly what are these favorable conditions? One very significant loss element to consider is the attenuation of the signal in the medium overlying a subsurface aquifer. Overlying ice (and soil) possess permittivities and conductivities very different from free space values and, as such, these media can significantly attenuate the sounding signal. As we demonstrate, the media conductivity has a fairly severe attenuating effect on medium frequency (MF) signals, with signal depth being inversely proportional to overlying medium conductivity.

Figure 1 shows the results of a multilayer wave propagation model displaying the MARSIS return signal strength from an aquifer ($K=81$, $\sigma = 10^{-3}$ S/m) located 3 km below an overlying ice layer. The 3 km depth is chosen to mimic a basal lake at the base of the polar ice deposits. MEX is located at 250 km above the cap and it is assumed ionospheric losses are negligible (sounding in the nightside). In the model the overlying ice layer has a relative permittivity $K=3$ and a conductivity that is treated as a free parameter varied in the analysis. The model includes the ray divergence, the ingoing and outgoing transmission coefficient at the surface and the reflection coefficient from the aquifer. The full, complex index of refraction was applied to determine the icy medium loss. The ice layer was assumed to be homogenous, ignoring reflections from stratified layering in the ice (see discussion in “Conclusions”). The anticipated aquifer-reflected return signal strength at MARSIS as a function of the overlying ice layer conductivity is the model output. The noise level in the figure is the cosmic background level of $\sim 6 \times 10^{-20}$ W/m²Hz (for a 1 MHz bandpass, this corresponds to 5 μ V/m). The 4 MHz signal is considered in the analysis. Modeling analysis and field tests suggests a transmitter power at these frequencies is between 5-10 W, and for this analysis here, we assume a 5W transmission.

As evident in the figure, return signals at 4 MHz exceeds the noise level from an aquifer embedding in a 3 km ice mass, as long as the medium conductivity remains below 10^{-5} S/m. For overlying ice conductivities above 10^{-5} S/m, very significant medium attenuation is expected which limits the ability of MARSIS to detect a deep highly-reflecting surface.

Figure 2 shows the MARSIS-to-Aquifer sounding range (the depth where the backscattered signal is above the $5 \mu\text{V/m}$ noise level) as a function of overlying ice conductivity. The analysis was run for two different MEX altitudes (250 km and 800 km). To obtain Figure 2, the model used to derive Figure 1 was rerun applying a range of aquifer depths and a range of MEX altitudes to create the

synopsis. Also shown are the conductivity ranges for permafrost, ice and snow [Daniels, 1996; Kirby and Hughs, 1996]. Note that as the ice conductivity increases, the aquifer must be located closer to the ice mass top for detection above cosmic background level. For ice conductivities $>10^{-3}$ S/m (consistent with highly conductive ice or permafrost) MARSIS is limited to detecting highly-reflecting layers in the first 100 meters of the ice cap. However, for the case where the overlying ice conductivity is low ($<10^{-5}$ S/m like firm snow) medium attenuation alone will not limit MARSIS penetration into the deep layers. The model indicates that the maximum aquifer detection depth, d , varies inversely with ice conductivity, $d = k/\sigma$, with k being 0.013 S and 0.006 S for 250 km and 800 km altitude, respectively.

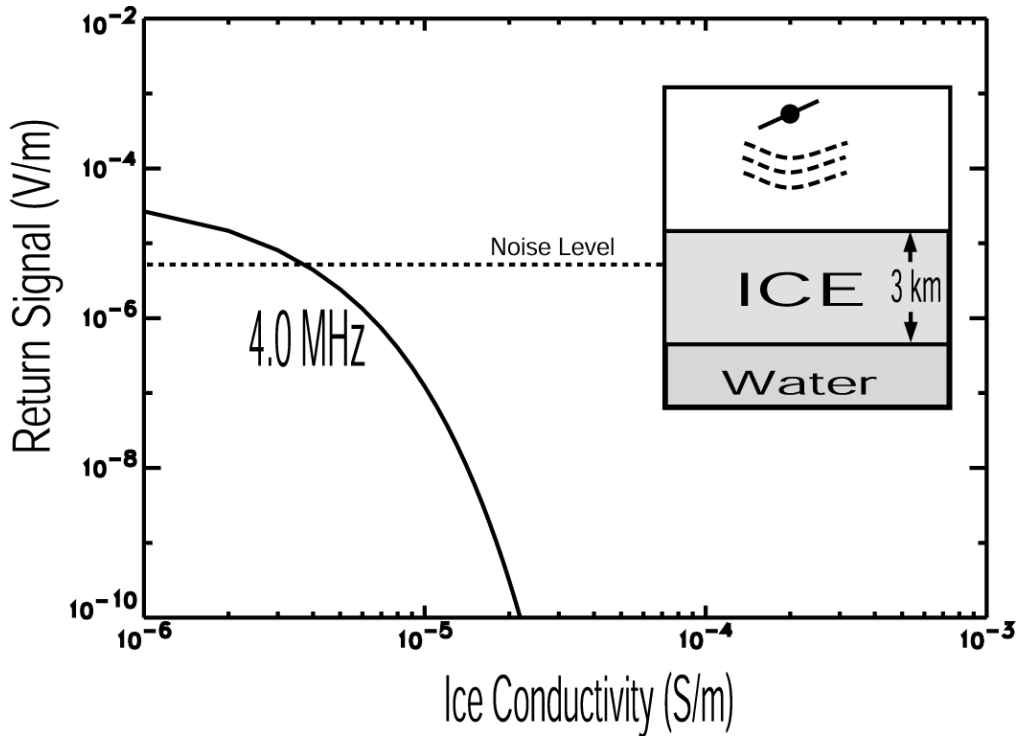


Figure 1. Return signal strength to MARSIS at 250 km from an aquifer at 3 km depth. The depth is consistent with the height of the polar ice caps. Note that the return signal becomes increasingly difficult to detect as ice layer conductivity increases.

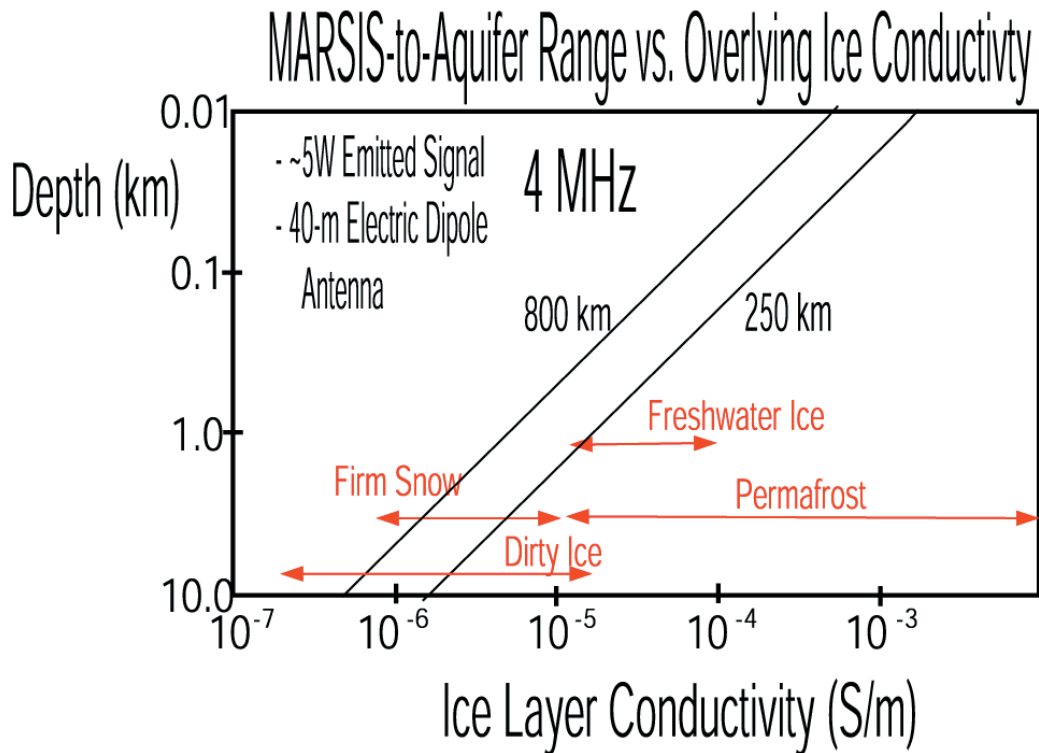


Figure 2. MARSIS range to aquifer for varying overlying ice conductivities. The line represents the aquifer depth and ice layer conductivity where a return signal just exceeds the noise level.

Figure 3 redisplayes the MARSIS-to-Aquifer range in Figure 2 onto an example polar profile (from Clifford et al. [2000]) of the northern polar mass. An 800 km MEX altitude over the pole is used. Note that for ice conductivities below 10^{-5} S/m, substantial penetration exceeding 500-m can occur and for ice conductivity below 2×10^{-6} S/m, MARSIS can essentially penetrate through the thickest portions of the ice cap. The requirement on the ice conductivity for making the transition from shallow to deep penetration is between 10^{-5} to 10^{-6} S/m (for MEX at 800 km). For higher conductivities ($>10^{-5}$ S-m), an examination of the cap base is still possible, but only in regions where the cap thins (cap edges, polar troughs, and Chasma Boreale and Australe) and signal attenuation is reduced. Similar results apply to the southern cap.

Given the seasonal deposition of dust onto the Martian polar cap, it is anticipated that the ice caps are “dirty.” Pure ice with lunar soil mixtures

at 1%, 10% and 50% fractional volume are found to have effective conductivities of $\sim 3 \times 10^{-7}$ S/m, $\sim 3 \times 10^{-6}$ S/m, and $\sim 2 \times 10^{-5}$ S/m respectively above 200° K (calculated from Figure 2 of Chyba et al [1998]). The lunar sediment consists of a partial metallic content, similar to expected Martian dust. Given the cleaner-appearing remnant ice on the pole top, we anticipate a low dust-to-ice ratio and medium conductive attenuation from this top layer alone may not limit signal penetration. However, the darker underlying layered deposits are believed to have an increased dust-to-ice ratio [Clifford, 1987] possibly beyond 50% fractional volume. If this is indeed the case, the effective conductivity will exceed 10^{-5} S/m and wave loss via medium attenuation could limit the signals from reaching the ice mass base. Conversely, the degree to which MARSIS signals penetrate the polar layered deposits may be used as a tool to indicate deposit dust-to-ice ratios.

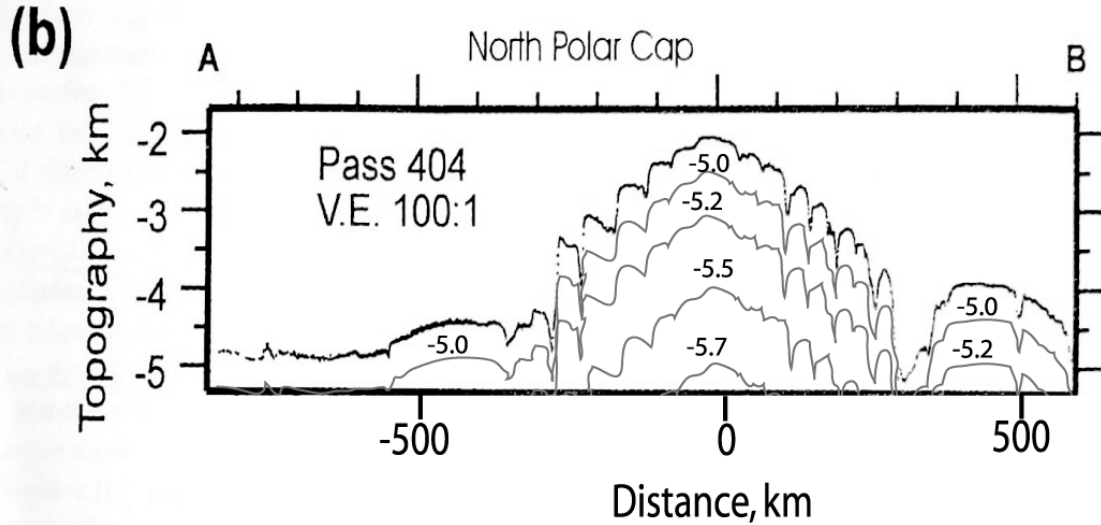


Figure 3. MARSIS north polar cap penetrations as a function of ice conductivity (Figure adapted from Clifford *et al.* [2003]). The log of conductivity is indicated with -5.0 equal to 10^{-5} S/m, and -5.8 equal to 1.6×10^{-6} S/m.

Conclusion

The analysis of Figure 1 was performed assuming a homogeneous ice layer. In fact, Mars polar ice is noted for its strata, and reflections from a number of such layers results in a loss in signal propagating to and from the aquifer surface. As such, the calculations above based only on medium conductive attenuation is an upper limit. For a conductivity below 10^{-3} S/m, the reflectance at a few MHz is primarily defined by changes in the permittivity between two layers, $R = (\epsilon_1^{1/2} - \epsilon_2^{1/2})^2 / (\epsilon_1^{1/2} + \epsilon_2^{1/2})^2$. If the permittivity change is only $\sim 10\%$ between layers, then the transmission through an individual interface is 0.9993. For 50 such stratified layers (100 encounters on the round trip) the power in the return signal is only reduced by -0.3 dB compared to the homogeneous case and strata reflections are essentially not significant. Conversely, if the permittivity change is extreme (50% at each interface), the propagation through 100 layers results in a -8.8 dB of loss compared to the homogeneous case. Since the permittivity of ice and basalt are very close, this second case is likely an over-estimate. We conclude this reflective loss is not as significant as medium conductive losses especially for the case $\sigma > 10^{-5}$ S/m.

“Bumpy” surface clutter can also decrease return signal strength and increase ambient noise [Biccari *et al.*, 2003]. However, due to glacial flow, the polar ice masses are anticipated to be relatively smooth and such clutter should not be a dominant signal loss process in these regions. Undulating polar features do exist possibly in association with glacial movement [Cutts *et al.*, 1979] but their slopes are relatively shallow. For example, sub-surface sounding of terrestrial glacier ice indicates that terrain-derived clutter is not a substantial loss; this even at shorter wavelengths than MARSIS that are more sensitive to surface features [Oswald and Robin, 1973; Robin *et al.*, 1977].

While there are many potential signal attenuation processes, we investigate here the signal propagation through a conductively lossy medium (ice) that is presumed to overlie a polar aquifer. The study itself is simple. It is well-known that ground/ice conductivity attenuates radar signals. However, the application of this concept to the MARSIS sounder, presented here as a feasibility study, is new and is designed to set the expectations for the radar. We find (a) that for low conductivities ($< 10^{-5}$ S/m), medium attenuation is mild and this process

alone will not limit MARSIS signal penetration deep into the polar ice cap (below 500-m depth). (b) The study indicates that the ice conductivity range between 10^{-5} S/m and 10^{-6} S/m is a critical range where the ice mass base goes from undetectable to detectable for the MARSIS low power sounder (as illustrated in Figure 3). (c) There is concern that the icy polar layered deposits may contain a large dust concentration to increase the effective conductivity above 10^{-5} S/m, thereby limiting a detection from the ice mass base. (d) We also find that the relationship of aquifer probing depth, d , varies inversely with medium conductivity, $d = k/\sigma$, with a MARSIS system in polar ice yielding $k \sim 0.01$ S. As long as surface clutter and reflective losses remain small, this equation yields an estimate of ice probing depth.

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